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Reliability Design Based on System Performance-Cost Trade-off for Manufacturing Facility

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Abstract. The objective of this paper is to provide a model for effective implementation of costing RAM management in the design and procurement of production facility considering the system cost-performance trade-off. This research proposes a two-step approach of costing RAM design and test of system RAM for production facility. In Step 1, a static model is proposed to find an initial system configuration to meet the required performance based on system RAM and LCC and analyzes the trade-off relationships between various factors of RAM and LCC. In the second Step, we developed time and failure truncated models for system reliability test and analysis. For the computational purpose, we developed computer programs and have shown the sample results. By the sample test run, the proposed model has shown the possibilities to provide a good method to analyze system performance evaluation for both design and operational phase. This model can be applied to a wide variety of systems not only for costing RAM of the production facilities but also for the other kinds of equipment.

Key Words : *reliability design and test, RAM, availability growth.*

1. INTRODUCTION

A reliability model for effective implementation in all the phases of life cycle of manufacturing equipment is developed considering facility life cycle starting with conceptual design, detailed engineering design, procurement of manufacturing equipment and finally going through use and maintenance phase before being discarded at the end. Figure 1 shows various phases of an equipment from definitional concept to operational and maintenance.

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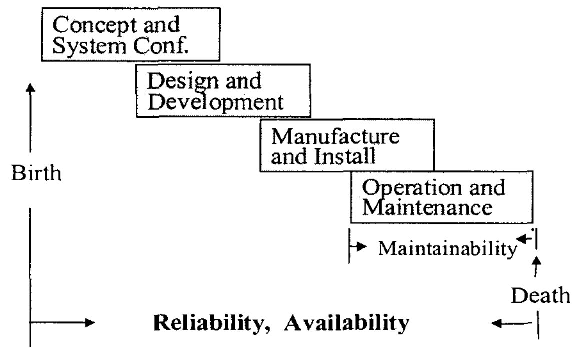


Figure 1. Equipment Life Cycle Phases

Truly, a reliability management program should be concerned itself with how to improve the system reliability from its birth-to-death process and its test (Misra K.B., 1992). Considering the occurrence of any failure during the lifetime of equipment, the system reliability can be rightly called birth-to-death process(Chisman J.A., 1998). In this study we consider a two-step approach as in Figure 2. In the first step, we considered a best system configuration design based on system RAM (reliability, availability and maintainability) and LCC (life cycle cost). In the second step, we developed two reliability test and analysis models which are the time and failure truncated. Generally reliability management system includes four areas such as 1) reliability design, 2) reliability estimating, 3) reliability test analysis and 4) reliability growth analysis. In this study we condensed these four areas into two-step approach.

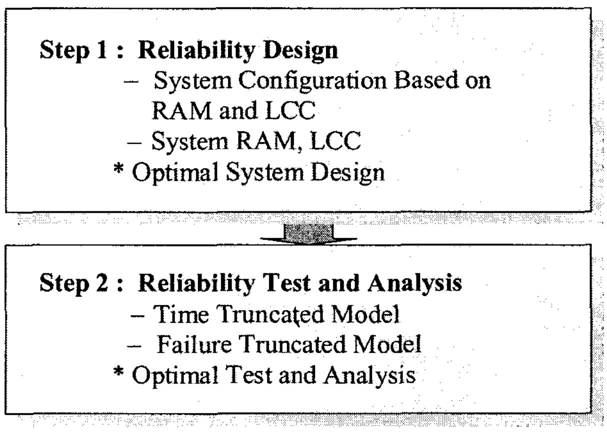


Figure 2. Two-step Approach of Costing RAM and Test

2. SYSTEM DESIGN BASED ON RAM AND LCC

2.1 System Design Based on RAM

In this step, the proposed model uses a step-by-step comparative approach considering the system performance factors in the design phase; such as RAM, LCC, and system configuration. In practice, when the failures happen and we repair or replace these equipments in order to get these into operational state, the maintenance costs incurred for repair or replacement depending on the system availability.

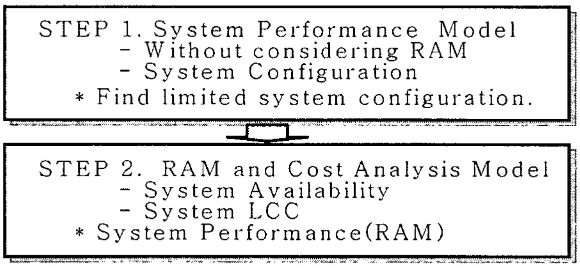


Figure 3. System Performance-Cost Model

Figure 3 outlines schematic steps of the system performance model which encompasses both analytic and simulation analyses. In the first step, a closed queuing network, CQN (closed queuing network) model is proposed to find the initial system configuration to meet the required system performance (production rate). This approach provides a full range of methods for a part and machine selection system configuration, and the material handling system selection. This model can be used to system design to satisfy the required RAM and LCC, or to find feasible production planning under a given system configuration. In second step, a stochastic model is developed to optimize the system in regard to RAM and LCC parameters. The schematic flow of proposed model is shown in Figure 4. In this study, we developed a program to find the system optimal configuration and to calculate system RAM and LCC. To compute the system reliability and maintainability, we have derived equations for MTTF, MTBF, $R(t)$, and MTTR and considered three types of maintenance policies: preventive maintenance(PM), corrective maintenance(CM) and also a combined type of these two. The equations, used for computing the system reliability $R(t)$ and maintainability $M(t)$ up to time t, are defined as follows:

$$R(t) = Pr[TTF \geq t] = 1 - F(t)$$

$$MTTF = E[TTF] = \int_0^\infty x \cdot f(x)\,dx\,,$$

MTTF is applicable to non-repairable systems, and MTBF is used in the same sense of MTTF for repairable systems.

$$M(t) = Pr[TTR \leq t] = \int_0^t g(s)\,ds = G(t)$$

$$\mathrm{MTTR} = \mathrm{E(TTR)} = \int_0^\infty y \cdot g(y)\,dy$$

where, MTTF : Mean Time to Failure,
MTBF : Mean Time Between Failure,
MTTR : Mean Time to Repair,
TTF : Time to Failure,
TTR : Time to Repair,
G( ) : Distribution function of TTR,
F( ) : Distribution function of TTF.

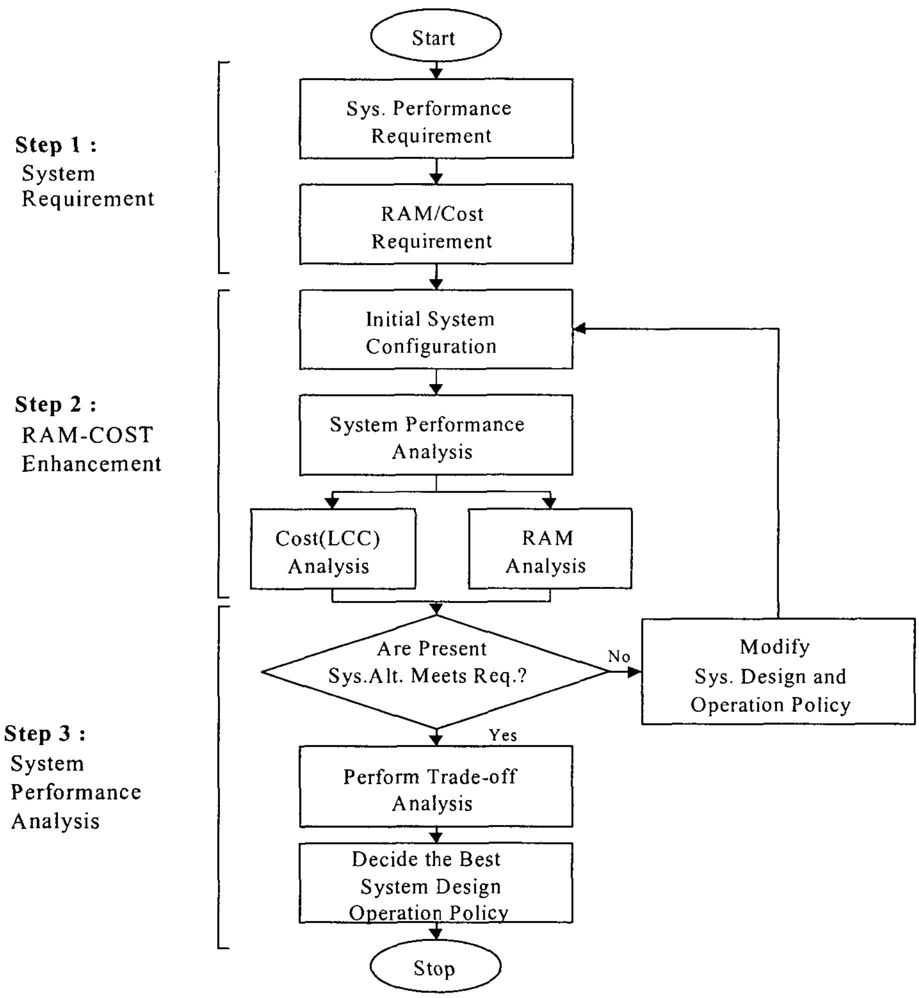


Figure 4. Schematic Flow of Proposed Model

In this research, we have developed a CQN model which is capable of changing the system configuration to meet the target performance(production rate). We have analyzed and improved the system configuration to find a set of system performances such as : the system configuration, production rate, average flow time. To make the CQN model more robust, we considered the system RAM and LCC in simulation. The decision making in system design is made generally on the basis of the required availability with minimum cost. In this research, we used a new tool for a cost-effective system design by considering system life cycle cost and its availability together. The equations for availability are given as follows:

$$A_t = \frac{\text{Total Uptime}}{\text{Total Uptime} + \text{Total Downtime}} \qquad \textit{during time interval (0,t)}$$

$$A_e = \lim_{t \to \infty} E\left[\frac{\sum_{i=1}^{U(t)} R_i}{\sum_{i=1}^{U(t)} R_i + \sum_{i=1}^{D(t)} D_i}\right] = \frac{E[R]}{E[R] + E[D]}$$

where, D_i : i^{th} down time interval,

R_i : random interval between ith and $(i-1)^{th}$ down time,

A_t : average availability during time interval $(0,t)$,

A_e : steady state or equilibrium availability,

$U(t)$, $D(t)$: the number of up and down time during $(0,t)$.

2.2 Reliability Costing

There are trade-off relationships between various availability growth factors (reliability and maintainability) and life cycle cost. In this research, the life cycle cost is defined as the sum of the acquisition costs, the discounted sum of maintenance costs, break-down repair costs, and logistics support costs during the period of intended use of the system. Mathematically, the total life cycle cost can be expressed by :

$$TCOST = \sum_{j=1}^{N}\left[\text{TCOST of Subsystem } j \text{ incurred during intended time}(0,t)\right]$$
$$= \sum_{j=1}^{N} TCOST_j$$

where, N : the number of subsystems

$TCOST_j$ = (Acquisition Cost) + (Discounted Sum of Maintenance Cost)
+ (Discounted Sum of Breakdown Repair Cost)
+ (Discounted Sum of Logistics Support Cost of Subsystem j).

The maintenance cost consists of corrective and preventive maintenance costs. The logistics support cost is given by the percentage overhead costs attributed to maintenance actions. The logistics support cost for subsystem j is given by :

$$(\text{Logistics Cost})_j = \alpha_1 CM_j + \alpha_2 PM_j$$

where, α_1 : percentage overhead cost for corrective maintenance,

α_2 : percentage overhead cost for preventive maintenance,

CM_j : corrective maintenance cost of subsystem j,

PM_j : preventive maintenance cost of subsystem j.

Thus, we can represent the total cost incurred during the intended time interval $(0,t)$ as :

$$TCOST_j = AC_j + DSCM_j + DSPM_j + \alpha_1 DSCM_j + \alpha_2 DSPM_j + DSRC_j$$
$$= AC_j + (1+\alpha_1)DSCM_j + (1+\alpha_2)DSPM_j + DSRC_j$$

where, AC_j : acquisition cost, $DSCM_j$: discounted sum of CM_j,

$DSPM_j$: discounted sum of PM_j,

$DSRC_j$: discounted sum of break down repair cost

Thus, the expected $TCOST$ can be given by :

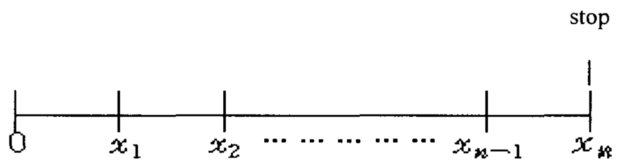
$$E(TCOST) = \sum_{j=1}^{N} \{AC_j + (1+\alpha_1)E(DSCM_j) + (1+\alpha_2)E(DSPM_j) + E(DSRC_j)\}$$

3. RELIABILITY TEST

In practice, there are usually limited test data available in the development and test phases of equipment and in most cases, the obtained data are failure and time truncated. To obtain the reliability goal for equipment under development or operation, we have to try through reliability design, estimation, test and reliability growth analysis, which is a process of design-test-fix-test-fix. There are several mathematical reliability prediction models proposed in the literatures(Vineyard M.L., 1992) This model assumes that the failures, during development test phase, follow the non-homogeneous Poisson process with Weibull intensity, $\lambda\beta t^{\beta-1}$.

3.1 Failure Truncated Model

In the test phase of equipment development, when the failure rate is reduced by a certain level, we can stop the test. For this case we can use this Failure Truncated Model Suppose that the data from a Weibull process are truncated at the n th failure yielding observed failure times. That is first n successive occurrence of a Weibull process. Now, we consider a successive occurrences of a single Weibull process and this follows non-homogeneous Poisson process.



Then the conditional density of x_i given by $X_{i-1} = x_{i-1}, \ldots\ldots, x_1$

$$F_i(x_i \mid x_1, x_2, \ldots, x_{i-1}) = 1 - \exp\left[-\left(\frac{x_i}{\lambda}\right)^{\beta} + \left(\frac{x_{i-1}}{\lambda}\right)^{\beta}\right]$$

$$f(x_i \mid x_1, x_2, \ldots, x_{i-1}) = \prod_{i=1}^{n} f_1(x_i, x_1, \ldots, x_{i-1})$$
$$= \left(\frac{\beta}{\lambda}\right)^n \exp\left[-\left(\frac{x_n}{\lambda}\right)^{\beta} \cdot \prod_{i=1}^{n}\left(\frac{x_i}{\lambda}\right)^{\beta-1}\right]$$

where, $x_1 \le x_2 \le \ldots\ldots \le x_n < \infty$

$f(\square)$: the probability density function of occurrence of n successive failures.
To estimate parameters, the likelihood function can be given by;

$$L = \left(-\frac{\beta}{\lambda}\right)^n \exp\left[-\left(\frac{x_n}{\lambda}\right)^{\beta}\right]\prod_{i=1}^{n}\left(\frac{x_i}{\lambda}\right)^{\beta-1}$$

The closed form of MLEs can be obtained by $\frac{\partial \ln(L)}{\partial \lambda} = 0$ and $\frac{\partial \ln(L)}{\partial \beta} = 0$,

These are $\hat{\lambda} = \dfrac{x_n}{n^{\frac{1}{\beta}}}$ and $\hat{\beta} = n \,/ \sum_{i=1}^{n-1} \ln\left(\dfrac{x_n}{x_i}\right)$. (3.1)

These estimates are joint sufficient statistics, and the ratios of the form x_n / x_i are distributed independent of λ and fixed β . x_n is sufficient statistics for λ . Thus x_n and such ratios are stochastically independent. The failure rate of i^{th} occurrence of failure is given as :

$$\rho_i(x_i) = \frac{\lambda}{\beta}\left(\frac{x_i}{\lambda}\right)^{\beta-1}$$

and MTBF is , $M_i(x_i) = [\rho_i(x_i)]^{-1} = \dfrac{\lambda^{\beta}}{\beta}\dfrac{1}{x_i^{\beta-1}}$ (3.2)

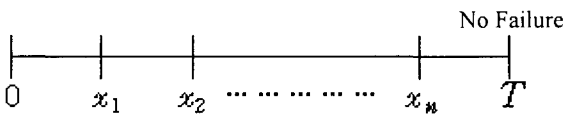
The reliability at i-th occurrence of failure is given by

$$R_i(x_i) = \exp\left[-\left(\frac{x_i}{\lambda}\right)^{\beta} + \left(\frac{x_{i-1}}{\lambda}\right)^{\beta}\right] \tag{3.3}$$

When we have met predetermined level of failure rate, we can finish test with the final failure rate, MTBF and reliability computed by failure truncated model.

3.2 Time Truncated Model

Let T be predetermined and suppose $n \ge 1$, then the failures are observed for the Weibull process during (O,T) at times $0 < x_1 < x_2 < \ldots\ldots < x_n$.



It is the case that the last in nth failure is observed at time x_n and that no failure are observed during (x_n, T). In this case we could get a little different likelihood function.

$$L = f(X_1, X_2, \ldots, X_n)(1 - F_T)$$

where, $F_T = F(T \mid X_1, X_2, \ldots, X_n)$.

thus, $L = \left(\frac{\beta}{\lambda}\right)^{\beta} exp\left[-\left(\frac{T}{\lambda}\right)^{\beta} \cdot \prod_{i=1}^{n}\left(\frac{x_i}{\lambda}\right)^{\beta-1}\right]$.

The MLEs of λ and β are given by

$$\hat{\lambda} = \frac{T}{n^{\frac{1}{\hat{\beta}}}} \quad \text{and} \quad \hat{\beta} = n / \sum_{i=1}^{n-1} l_n\left(\frac{T}{x_i}\right) \tag{3.4}$$

The achieved MTBF at time T is given by $M(T) = \frac{\lambda^{\beta}}{\beta}\frac{1}{T^{\beta-1}}$. (3.5)

4. MODEL APPLICATION

We developed computer programs for both reliability design and testing. These programs were applied to a set of sample problems and were known to be useful for both reliability and life cycle cost trade-off. For the illustration purpose, a sample system, automobile parts manufacturing facility consisted of 4 workstations is illustrated in the block diagram shown in Figure 5. The example facility is consisted of four work stations as ; 1) molding process, 2) cutting process, 3) heat treatment process and 4) packing process. The system produces two types of parts. The required production rate is given by 7 unit/hour at 100% system availability and the production ratio for both part type A and B is 3 : 2. First we demonstrated the system configuration design using RAM and LCC-based model as shown in chapter 2 and then demonstrated the reliability test of the system from the design phase to operating phase as given in chapter 3.

4.1 System Configuration and RAM

In this step, we have analyzed and improved the system configuration to find a set of conditions for better system performance. In this step, we can make two kinds of trade-offs : 1) to find the optimal system configuration to satisfy the required production rates, 2) to find the optimal production planning (product mix) with a given system configuration. Figure 6 shows sample output of the initial system configuration which is consisted of one machine at each workstation without considering RAM and cost parameters.

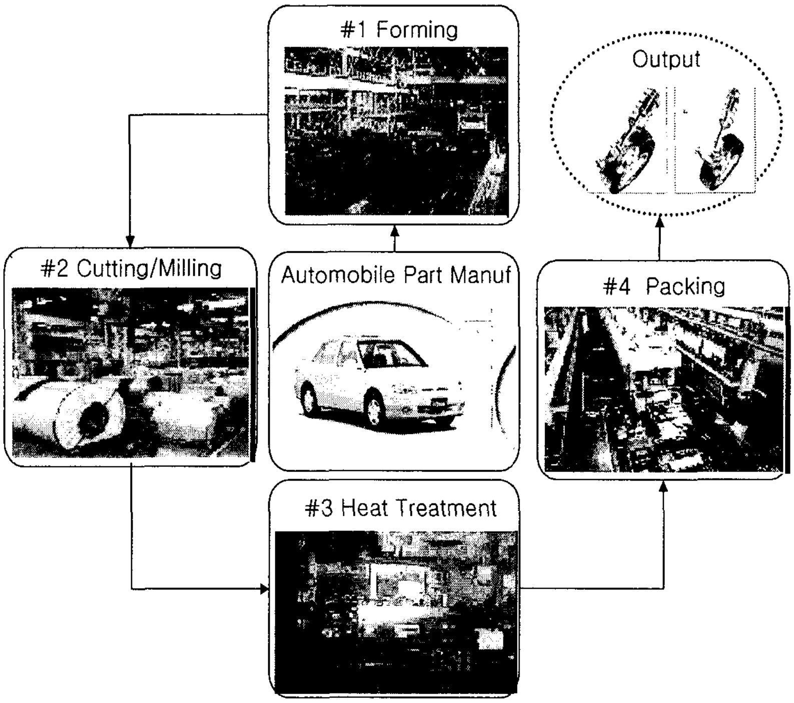


Figure 5. Sample System

```
-------------------------------------------------------------------------------
SAMPLE PROBLEM(INITIAL CONFIGURATION)  June 25, 2001.
-------------------------------------------------------------------------------
  SYSTEM PERFORMANCE MEASURES:
  PRODUCTION RATE =    2.8076   ITEMS PER HOUR
  PRODUCTION RATES BY PRODUCT TYPE
                   NUMBER        VALUE
        PRODA        1.684        505.188
        PRODB        1.123        224.524
        TOTAL VALUE =   729.715
-------------------------------------------------------------------------------
```

Figure 6. Sample Output of Initial System Configuration

4.2 RAM Cost

To make the model more robust, we developed simulation model for the system RAM and LCC. The sample outputs of RAM and LCC for initial and final system configuration are shown in Figure 7, and the outputs are summarized in Table 1.
The impact of system RAM and LCC on the system performance growth is very serious. The production rate of the final system is 6.250 unit/hr in Step 2 where availability growth activities are considered for the system performance growth. The sample outputs of the example system are compared with that of five system alternatives. The system

configuration of each alternative is computed by CQN model which does not consider the RAM and cost parameters but only the production process time factors.

```
RAM AND LCC ANALYSIS(FINAL SYS.)
                        25, June, 2001
SYSTEM AVAILABILITY :  .8598281
COST RATE : 1.9205410 W PER HR
LCC/UNIT :   0.3073 W PER UNIT
PW OF LCC : 8258.3260 W

SYSTEM COST:
   TOTAL CAPITAL COST. 1800.000 W
   OPERATING COST:
   TOTAL CM COST... 4034.896 W
   TOTAL PM COST.... 146.627 W
   TOTAL MATERIAL COST...476.803 W
```

```
RAM AND LCC ANALYSIS(INITIAL SYS.)
                        25, June, 2001
SYSTEM AVAILABILITY :  .5669794
COST RATE : 1.5976960 W PER HR
LCC/UNIT :   1.0042 W PER UNIT
PW OF LCC : 8258.3260 W

SYSTEM COST:
   TOTAL CAPITAL COST. 1800.000 W
   OPERATING COST:
   TOTAL CM COST... 4034.896 W
   TOTAL PM COST.... 146.627 W
   TOTAL MATERIAL COST...476.803 W
```

Figure 7. Sample Output of RAM and LCC of Initial and Final Systems

Table 1. Comparison of Output by Alternative

Availability Costing Factors	Alt. #1 (Initial Sys.)	Alt. #2	Alt. #3	Alt. #4	Alt. #5 (Final Sys.)
System Configuration	1,1,1,1,1	1,2,1,1,1	1,2,2,1,1	1,3,2,1,1	1,3,2,2,1
System Availability	0.5669	0.6275	0.7121	0.7935	0.8598
LCC	4,537.45	5,432.12	6,230.31	7,9541.72	8,258.32
Cost Rate(LCC/Unit)	1.597	1.685	1.772	1.867	1.920
LCC/unit Product	1.004	0.567	0.418	0.341	0.307
Production Rate	1.591	2.972	4.235	5.495	6.250

For this configuration, we considered RAM and cost factors to find the system availability LCC and production rate. The decision making in manufacturing system design is made generally on the basis of the required availability with minimum cost. Therefore, in this research we used a new tool for a cost-effective system design by considering LCC and its availability together. Figure 7 shows the sample outputs of RAM and LCC analysis of both the initial and final system. We used a system performance index(SPI) such as present worth of LCC, system availability, LCC per system availability, LCC/unit product and production rate. The results are summarized in Table 1.

4.3 Reliability Growth Test

A reliability growth test phase of the above system has been applied for *T=200* hours. From the test data up to time 200, we computed the parameter estimates, $\hat{\lambda}, \hat{\beta}, \hat{M}(200)$, and these 90 percent confidence intervals. The observed failure times t_i are given by;

$(n = 21)$: 2.2, 3.3, 4.5, 5.3, 5.8, 20.3, 27.4, 34.1, 55.2, 58.4, 61.4, 61.4, 62.2, 78.3, 78.4, 91.9, 97.7, 112.4, 116.9, 142.4, 176.8, 181.5

By the equation (3.1), (3.2) and we found the following outputs using the computer program developed. Figure 8 shows the sample output of reliability growth test.

$$\hat{\lambda} = 1.16\ ,\ \ \hat{\beta} = 0.59 \ \text{ and } \ \hat{M}(200) = 16.11$$

```
------------------------------------------------------------------------
THE RESULT OF PARAMETER ESTIMATE
(TIME TRUNCATED)
------------------------------------------------------------------------
  LAMDA =  1.16
  BETA  =  0.59
  90.0 % CONFIDENCE BOUND OF LAMDA IS    ( 0.29, 3.42 )
  90.0 % CONFIDENCE BOUND OF BETA IS     ( 0.37, 0.78 )
------------------------------------------------------------------------
RELIABILITY, FAILURE RATE AND MTBF
------------------------------------------------------------------------
  FAILURE RATE  =   0.06
  MTBF          =  16.11
  RELIABILITY   =   0.69
------------------------------------------------------------------------
```

Figure 8. Sample output of reliability growth test

5. CONCLUSIONS

This research proposed a two-step effective model of RAM design and reliability test for manufacturing equipment acquisition. In Step 1, a static model is proposed to find an initial system configuration to meet the required performance based on system RAM and LCC. In the second Step, we developed time and failure truncated model for system RAM test. A sample problem of manufacturing equipment acquisition was run by proposed model. The proposed model will provide a good tool to analyze system performance evaluation for both design and operational phase. Furthermore, it can be extended easily for various problems solving with a variety form of outputs. In this study, we have developed a model to find the best maintenance policies for both system designers and operators to provide how they can solve their design and maintenance problems. Also this study is intended to find the system production capability in trying different design and maintenance policies for both system designers and operators to construct a cost efficient system within appropriate system design and maintenance policies. We developed Computer programs to support the model and applied to a sample problem. The results show that the proposed method is powerful enough to find the best maintenance policies to meet the required production rate.

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